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전력 설비 감시를 위한 무선 센서

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Wireless Sensor for Diagnostics of Electric Equipments

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Abstract : Methods and analysis of a simple wireless sensor concept for detecting and locating faults as well as for load monitoring are presented. The concept is based on distributed wireless sensors that are attached to the incoming and outgoing power lines of secondary substations. A sensor measures only phase current characteristics of the wire it is attached to, is not synchronized to other sensors and does not need configuration of triggering levels. The main novelty of the concept is in detecting and locating faults by combining power distribution network characteristics on system level with low power sampling methods for individual sensors. This concept enables the sensor design to be simple, energy efficient and thus applicable in new installations and for retrofit purposes in both overhead and underground electrical distribution systems.

Key Words : Load monitoring, Wireless sensor, Power distribution

1. Introduction

A short circuit in a network branch is assumed if the phase current reaches a magnitude above a threshold and stays above that threshold level for at least a certain duration in time. Wireless sensors that are attached to incoming and outgoing power lines of substations can record this event. By comparing the sensor readings of the three phases in subsequent locations, the faulty line segment is located.

In networks with an ungrounded neutral, the fault current is basically composed of the currents flowing through the earth capacitances of the sound phases. In a 20 kV overhead network with zero fault resistance, the fault current is approximately 0.07 A/km [1]. This type of earthing is quite common in the Nordic countries. Some systems have a compensated neutral (called Petersen coil system). The aim with the compensation is to cancel the system earth capacitance by connecting an equal inductance to the neutral [1]. Hence, the earth fault current decreases correspondingly. In the case that the inductance is tuned to exactly match the system capacitance, the fault current will contain only a small resistive component. In practice, however, the network is slightly under- or overcompensated, at 95% or 105%. This type of earthing is common in Continental Europe. Solidly earthed distribution networks are used in the United States, for instance. In these, the single phase to earth fault current varies with the fault location and the fault resistance.

The properties of detecting and locating earth faults depend basically on the type of earthing and on the network topology. The location is generally determined by the characteristics of the zero sequence current I_0, the neutral voltage U_0, and the phase shift between I_0 and U_0. Wireless sensors that participate in activities to detect and locate earth faults should, therefore, have capabilities to concurrently measure current and voltage of the three phases in one location, so that the sum current in that network point can be determined.

Some prior art wireless sensor solutions have solved these issues by using specific hardware design [2], by constantly measuring and reporting phase current and voltage [3], or by synchronizing sensors using the Global Positioning System, GPS [4].

There are a number of disadvantages with these solutions. Continuous monitoring and reporting draws a great amount of energy. This energy may not be available and the activity of a sensor should be tuned accordingly [5]. GPS provides very accurate time synchronization, but is expensive and has high energy dissipation compared to other standard components used in wireless sensors of today [6]. Using specific hardware is an error prone alternative that is sensitive to installation and calibration precision.

Arranging reliable voltage measurements is also problematic in a number of ways. The most feasible means seems to be a voltage divider based on a capacitive principle involving the phase wire and the earth capacitance. This solution has a number of drawbacks. A cable network can not be retrofitted with the voltage sensors as it is prohibited to put any items on the sleeve of cable terminations or joints. The capacitor will have to hang in the air on a distance from the cable. The other two parallel phases and the cround capacitance will then greatly affect the reliability and sensitivity of the measurement, even if the phenomenon is computationally compensated for. The same is recognized in overhead power line systems as well, especially when the phase angle should be determined.

In this paper, methods and analysis of a simple wireless sensor concept for detecting and locating faults as well as for load monitoring are presented. The concept is based on distributed wireless sensors that are attached to the incoming and outgoing power lines of secondary substations. A sensor measures only phase current characteristics of the wire it is attached to, is not synchronized to other sensors and does not need configuration of triggering levels. The main novelty of the concept is in detecting and locating faults by combining power distribution network characteristics on system level with low power sampling methods for individual sensors. Different sampling methods are assessed in the concept framework and test results with a prototype implementation are discussed

2. System Design

The system architecture being considered is illustrated in Fig. 1, where PS stands for the primary substation, SA and SB for secondary substations and NCC for the network control center. A secondary substation has wireless sensors attached to incoming and outgoing medium voltage power conductors. The dark gray circles on every power line phase illustrate this.

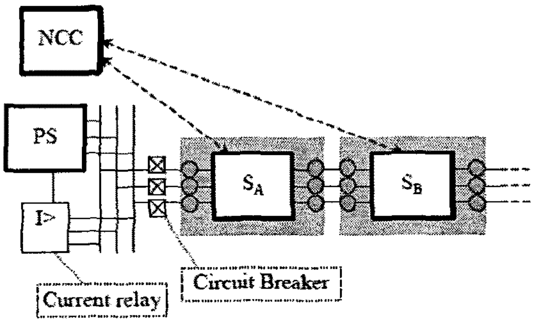

Fig. 1. A view of the system hierarchy. *PS* stands for the primary substation, *SA* and *SB* for secondary substations and *NCC* for the network control center.

The gray boxes surrounding a secondary substation show to which substation different sensors belong. Secondary substations are assumed to have communication capabilities so that they can either communicate with each other, with the primary substation or with the network control center.

Load tapping occurs only at substations. Load monitoring has briefly been described in the previous section. From the viewpoint of the system concept it is rather trivial to implement, thus it is not further discussed here. Detecting and locating faults by using distributed sensors that are unsynchronized and only measure phase current, is however challenging. The required system level methods needed for detecting and locating short circuits and single phase to earth faults are therefore addressed next.

2-1 Fault Detection

A sensor measures the phase current characteristic only, thus a fault can be determined based on only changes in the phase current amplitude and phase shift. This implies that to detect a fault, a sensor must frequently sample the current and compare its characteristics to pre-set trigger levels. Sampling draws energy, and configuring trigger levels for different network topologies, is a very demanding task.

Another method that does not require frequent sampling or complex configuration is introduced. A sensor stores the measured current characteristics in a FIFO buffer of length N. Let T be denoted the period of the fundamental power frequency, t a specific fundamental power frequency period in the time domain, and i(t) the current amplitude for t. If the current is sampled with a steady cycle of T, a buffer will contain amplitude samples i(t) ?i(t-(N-1)T). A fault is not recognized until the sensor measures a current signal of zero (or close to zero). This happens when the protective relays in the primary substation (see Fig. 1) trip and cause the circuit breaker of the faulty line to open. When a sensor measures this loss of load current, it assumes that a fault has occurred. If the buffer size has correctly been chosen, the buffer will contain measurements of the current before the fault and after the fault transient has occurred (denoted current during the fault).

The buffer contents is then transferred to the substation data concentrator for further processing. If the phase current amplitude drops due to some other reason than a fault, and sensors send their buffer contents as a consequence of this, this error is recognized at the primary (or secondary) substation level that owns information about the occurrence and cause of events.

2-2 Locating single phase to earth faults

Locating single phase to earth faults is more problematic than locating short circuits. The incremental fault current vector may not dominate the current measurements during the fault as much as in a short circuit case. The fault current depends on network earthing, phase to ground capacitances, fault resistance and network topology.

The fault locating method proposed in this paper originates from the theory of differential relays. Consider the network with an ungrounded neutral in the upper part of Fig. 2 and the network with a compensated neutral in the lower part of Fig. 2. The figure shows three phases of a power line, depicted 1, 2, and 3. Sensors are the black boxes at locations A, B, and C. The dotted lines denote the path of the fault currents. The gray areas show the fault current distribution that originates from the evenly distributed earth capacitances of phase wires. Assume that an earth fault has occurred between A3 and B3. When the primary substation opens the circuit breaker, the data from sensors A1 to C3 will be available. The data of interest is the amplitude of the fault current and it should therefore be extracted from the samples. If S[i(α)] is a sample of the current before the fault, and S[i(β)] a sample of the current during the fault of sensor S, and if . is the phase shift between the samples, the fault current amplitude (expressed as Δ.i(S)) can be calculated

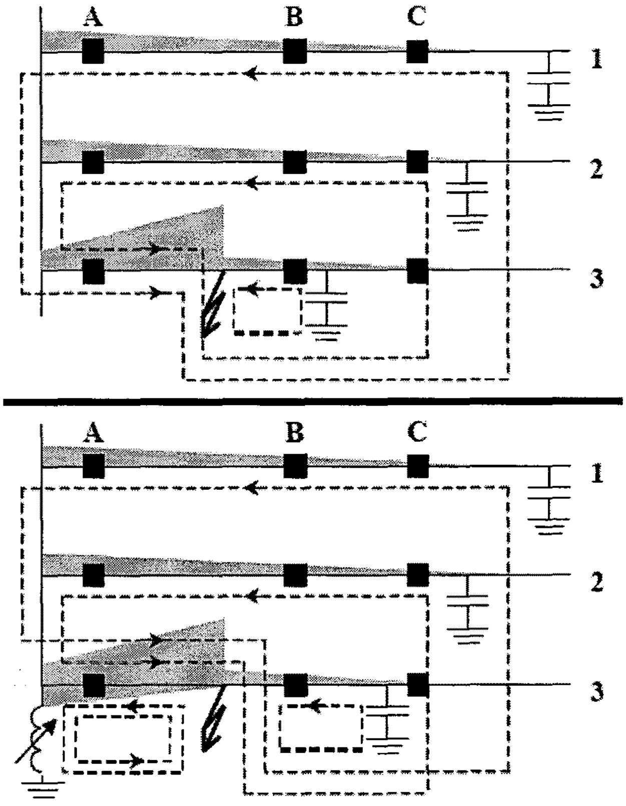

Fig. 2. Illustration giving the location of sensors (black boxes), fault current path (dotted lines) and the distribution of fault currents (gray areas) for a single phase to ground fault with ungrounded neutral (upper part) and compensated neutral (lower part) networks.

The feasibility of the method was verified with the EMTPATP network simulator. A 20 kV network with 6 parallel lines of 50 km each was simulated for ungrounded and 95% compensated network with fault resistance from 0 Ω to 5000 Ω.

3. Experiments

A wireless sensor prototype was developed to test the accuracy and power consumption of the Fourier and peak sampling methods. The main components of the prototype were a microcontroller, a short-range radio transceiver and a transducer interface with a Rogowski coil that was used to measure the conductor current.

The signal end of the coil was connected to a simple lowpass Butterworth filter and amplified before it was sent to the 10-bit A/D converter (step of 2.1 mA) of the microcontroller. The chosen microcontroller was PIC 16F877 with power down current consumption of 1 μA and active current consumption of 2 mA. The current consumption of an inactive (sleeping) sensor was measured to 10 μA, which was mainly drawn by the DC-DC converter, amplifiers and other active components. Three sensor prototypes were built (hereafter Sensor 0, *Sensor 1 and Sensor 2) and the following three* measurement tasks were tested:

Task (1) - peak sampling Sleep; wake up at the interrupt from the load current zero crossing; sleep for 90 electrical degrees; sample the current amplitude; return to sleep.

Task (2) - double peak sampling Sleep; wake up at the interrupt from the load current zero crossing; sleep for 90 electrical degrees; sample the current amplitude; go back to sleep; wake up at next zero crossing; sleep for 90 electrical degrees; sample the current amplitude; calculate the average of the first and second sample; return to sleep.

Task (3) - *Simple Fourier algorithm Sleep*; wake up at the interrupt from the load current zero crossing; wake up at 30, 90, 150, 210, 270, and 330 electrical degrees and sample the current, otherwise sleep; return to sleep.

Keeping the sensors in sleep mode between events minimized the current consumption. Hence, sensor activity was controller with two external interrupts, the zero crossing and a timer that was set according to the sampling pattern. The assessed period between task execution (Tper) was from continuous measurements (20 ms, k = 1) up to 300 ms between measurements (k = 15).

4. Results and Discussion

Fig. 3 shows the average current consumption of a sensor during tests of different tasks and different periods between the tasks. The Fourier algorithm that utilized only 6 samples consumed, despite the low number of samples, significantly more current than the simpler peak sampling methods. With the peak sampling methods, the sleep current dominated the current consumption when the period between measurements was longer than 60 ms. With the Fourier algorithm, the average current consumption was still 30 μA with a period of 100 ms (the longest feasible period between measurements as discussed above). Considering the fact that 6 samples is a minimum realistic number of samples with the Fourier algorithm, a microcontroller with lower operating current dissipation should be used in the implementation of the algorithm. This feature becomes especially important when considering that 16 samples or more are needed to effectively remove harmonics and imaging frequencies of a signal that first has passed a low order analogue filter.

The accuracy of the sampling methods was evaluated in a total of 9 tests. A test lasted 6 hours and the sensors (one per phase) sampled the current with a measurement period Tper of 80 ms. The measured current was averaged for every minute of a test and compared to the average minute current measured by a LEM Topas 1000 power quality analyzer. The experimental system had a load current of approximately 2.4 A and the total harmonic distortion was 8% with the third harmonic at 5% and the fifth at 6%.

Because the accurate physical characteristics of the Rogowski coils were not known and the sensors were not precisely calibrated, a difference between the current measured by a sensor and by the analyzer was recorded. This is illustrated in Fig. 4 (sampling according to Task (1)) where also some disturbances in the sensor reading can be noted after 5 hours, where sampling is done according to Task (3). The average difference for Task (1) and Task (2) was approximately 2 - 3%, and with the

Fourier algorithm 1%.

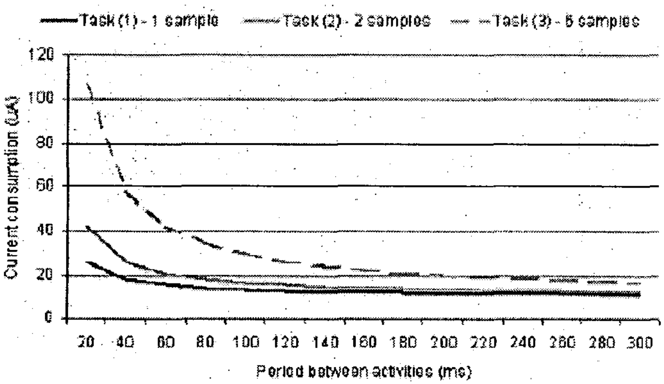

Fig. 3. Average current consumption of a prototype sensor with different sampling behavior and measurement periods.

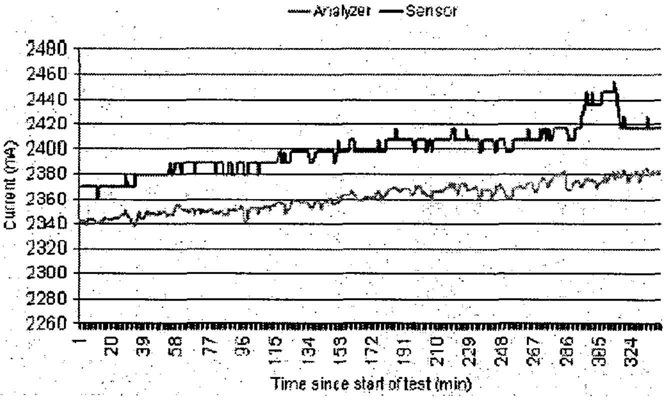

Fig. 4. Per minute current measured by a sensor (Sensor 0) and the analyzer during the test run of Task (1) at 10.10.2003.

5. Conclusions

A wireless sensor concept for load monitoring and fault management of electrical distribution networks has been presented. The concept is based on distributed wireless sensors that are attached to incoming and outgoing power lines of secondary substations. A sensor measures only phase current characteristics of the wire it is attached to, is not synchronized to other sensors and does not need configuration of triggering levels. However, current measurements made by these sensors are shown to be useful in fault management.

This is achieved by analyzing the trend of the difference in measurements made before and during a fault. Trend analysis requires, however, accurate measurements, especially for earth fault analysis. The fault current due to earth capacitances is very small in compensated networks, (some mA/km) and this sets requirements on the sampling accuracy. The accuracy that can be achieved depends on the components that are used in the sensor design, the sampling method and the energy that is available.

[Acknowledgement]

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